A Modification and Analysis of Lagrangian Trajectory Modeling and Granular Dynamics of Lunar Dust Particles

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Abstract

A previously developed mathematical model is amended to more accurately incorporate the effects of lift and drag on single dust particles in order to predict their behavior in the wake of high velocity gas flow. The model utilizes output from a CFD or DSMC simulation of exhaust from a rocket nozzle hot gas jet. An extension of the Saffman equation for lift based on the research of McLaughlin (1991) and Mei (1992) is used, while an equation for the Magnus force modeled after the work of Oesterle (1994) and Tsuji et al (1985) is applied. A relationship for drag utilizing a particle shape factor (ϕ = 0.8) is taken from the work of Haider and Levenspiel (1989) for application to non-spherical particle dynamics. The drag equation is further adjusted to account for rarefaction and compressibility effects in rarefied and high Mach number flows according to the work of Davies (1945) and Loth (2007) respectively. Simulations using a more accurate model with the correction factor (ϵ = 0.8 in a 20% particle concentration gas flow) given by Richardson and Zaki (1954) and Rowe (1961) show that particles have lower ejection angles than those that were previously calculated. This is more prevalent in smaller particles, which are shown through velocity and trajectory comparison to be more influenced by the flow of the surrounding gas. It is shown that particles are more affected by minor changes to drag forces than larger adjustments to lift forces, demanding a closer analysis of the shape and behavior of lunar dust particles and the composition of the surrounding gas flow.

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Key Point #1

CFD (Computation Fluid Dynamics) or **DSMC** (direct simulation Monte Carlo)

CFD: Sophisticated COTS Software to Solve *Navier Stokes Equation*, which describes motion of a gas or liquid

Gas:
- *Density*
- *Velocity*
- *Temperature*

Particle Ballistics Simulation

Generates *Particle Trajectories*

Particle:
- *Diameter*
- *Initial Starting Point*

Particle:
- *Forces*
- *Acceleration*
- *Velocity*
- *Position*

Key Point #2

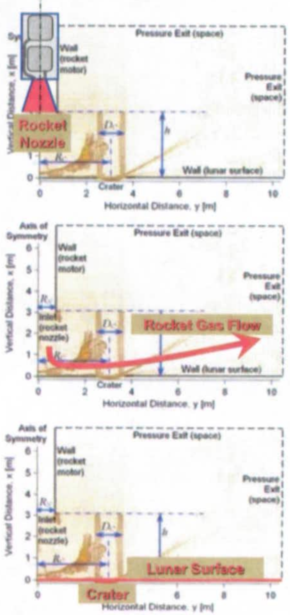
Assumption:

Ballistics calculations ignore the temporal variation of the gas.

Time Scale of Lander Descent >> Time Scale of Particle Trajectory

This is analogous to ignoring the effect of *grass growing* along the path of a golf ball rolling across a putting green

CFD Model Geometry (2D)



2nd Order Taylor's Series Trajectory Algorithm

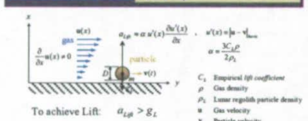
$$v_n = v_{n-1} + \Delta t\, a_{n-1}$$
$$r_n = r_{n-1} + \Delta t\, v_{n-1} + \tfrac{1}{2}\Delta t^2 a_{n-1}$$
$$a_n = F(r_n, v_n)/m$$

Particle Lift Model

Simple Model

Vertical Gradient of Horizontal Force ≠ 0
⇒ *Bernoulli* Lift Force

If any one of these 3 quantities go to 0, the *Bernoulli Lift Force* also goes to 0	• *Relative gas velocity* • *Vertical gradient of relative gas velocity* • *Gas density*

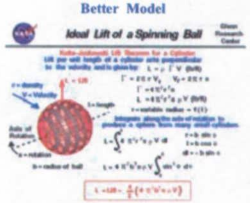


$$a_{Lift} = \alpha\, u'(x)\frac{\partial u'(x)}{\partial x}, \quad u'(x) = |u - v|, \quad \alpha = \frac{3C_L\rho}{2\rho_L}$$

C_L Empirical lift coefficient
ρ Gas density
ρ_L Lunar regolith particle density
u Gas velocity
v Particle velocity

To achieve Lift: $a_{Lift} > g_L$

Better Model



Using the method described above, integrated along a sphere's horizontal axis and arrived at an expression that includes two terms:

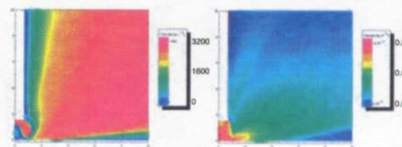
Lift force, $F_L = 8\pi\rho b^3 (u - v)\left(\omega_b + \frac{1}{2}\frac{du}{dy}\right)$

where,
u = the gas velocity
v = particle velocity
ρ = gas density
b = particle radius
ω_b = sphere's angular rotation speed
du/dy = vertical gradient of horizontal component of gas speed

- The 1st term looks like the **Magnus force**, the 2nd term looks like the **Saffman force**.
- If $\omega_b = -1/2\ du/dy$, then there is no lift, as would be expected.

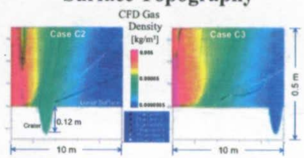
CFD Results (Case C2)

CFD Gas *Velocity* [m/s] CFD Gas *Density* [kg/m³]

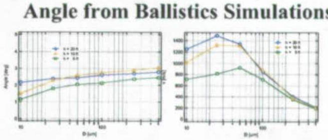


Height of Nozzle above Surface, *h*	Distance from Nozzle Center Line to Crater Center, R_c: 10 ft	30 ft
5 ft	Case C2	---
10 ft	Case C7	Case C3
20 ft	Case C1	---

Trajectory Dependence on Surface Topography



Estimated Dust Ejection Speed and Angle from Ballistics Simulations



Particle trajectory angles relative to ground for various particle sizes and CFD cases.

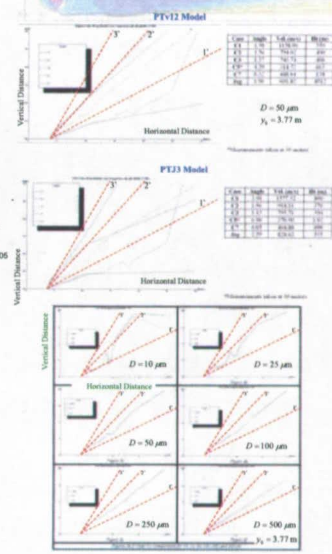
Particle speeds exiting the CFD model boundary.

Trajectory Models Simulated

- **PTv12** - Original / Lane and Metzger (Mar 2008)

Long and Metzger (Jun - Aug 2008)

- **PTJ4** – Drag Modifications: Haider & Levenapiel Model with Richardson & Zaki Correction Factor. This version of the code modifies drag force equations only.
- **PTJ5** – Lift Modifications: Extended Saffman Lift Force. This version of the code modifies lift equations only, and the extended Saffman lift equation.
- **PTJ3** – Drag / Lift Modifications: This version merges PTJ4 and PTJ5.
- **PTJ6** – Drag / Lift Modifications: Compressibility/Rarefaction Effects with Haider & Levenapiel Model, Magnus Effect, and Extended Saffman Lift Force.



Summary

Point #1

Ballistic Angles of simulated particle trajectories ≈ **Trajectory Angles** derived from Apollo video analysis

Points #2

- Craters can generate a substantial disruption to particle ballistics motion.
- Particles can easily fall into craters.
- Particle motion down-stream from craters, at the surface layer, may be suppressed.

Points #3

Comparison of Integration Algorithms

- **2nd Order Taylor Series** algorithm is very stable and well suited for single particle simulations, as long as the step-size is sufficiently small.
- **Beeman's Method** is Much Better
- **RK4** is superior to both

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1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
28-10-2008	Conference Presentation	10/28/08-10/31/08

4. TITLE AND SUBTITLE
A Modification and Analysis of Lagrangian Trajectory Modeling and Granular Dynamics of Lunar Dust Particles

5a. CONTRACT NUMBER
NAS10-03006

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
John Lane, ASRC Aerospace
Philip Metzger, NASA

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
ASRC-24

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NASA

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA/KSC

11. SPONSORING/MONITORING REPORT NUMBER

12. DISTRIBUTION/AVAILABILITY STATEMENT

13. SUPPLEMENTARY NOTES

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19b. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			John Lane
					19b. TELEPHONE NUMBER *(Include area code)*
					(000) 867-6939